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Comparison study of existing bowl piston and modified bowl piston diesel engine performance emission and combustion characteristics by using diesel

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ABSTRACT

In this investigation, the Modified bowl piston (MBP)diesel engine performanceemission and combustion characteristics have been studied by using diesel (100%D)and compared with theExisting bowl piston (EBP). From the results, it is evident that the MBP has given higher brake thermal efficiency (BTE) at an engine load 80%, 100% and higher exhaust gas temperature (EGT) has been given in engine all loads, when compared with EBP. In emission point of view,the MBP has given lower hydrocarbon (HC),carbon monoxide (CO), smoke at all loads when compared with EBP, However nitrogen oxide (NO_X), carbon dioxide (CO_2)have increased for MBP. In the combustion point of view MBP has given higher cylinder pressure (CP) and higher cumulative heat release rate (CHRR) at full load condition when compared with EBP. From the experimental results, it has been concluded that the MBP is anapt one in performance, emission and combustion perspective when compared with EBP by using 100%D.

Indexing terms / Keywords

Diesel engine; Performance; Combustion; Emission; Existing bowl piston; Modified bowl piston;

Academic Discipline and Sub-disciplines

Engineering and Mechanical Engineering

SUBJECT CLASSIFICATION

Engineering Materials

TYPE (METHOD/APPROACH)

Experimental Investigation

1. INTRODUCTION

For many years, the problem faced by the world is diesel engine exhaust gas emission. The increasing the engine exhaust gas emission is due incomplete combustion of air-fuel. The increase in engineexhaust gas emission is due to incomplete combustion of air-fuel. The high level exhaust gas emission creates many problems for human, others' lives and the same shall be controlledas well it is a big challenge in now a days. A big relief is that this can be controlled HC, CO, NO_x and smoke particles are main pollutants in engine exhaust gas emissions and they entirely depend on thecombustion of air-fuel which in turn depends on the shape of combustion chamber in the piston. Many literatures [1-11] have confirmed that exhaust gas emission level can be reduced and controlled by changing the piston combustion chamber's configuration. This investigation has been focused to minimize the emission level in the engine exhaust gas. Prasad et al. [1] have studied experimentally and analytically about different piston combustion chamber geometries. From their study they have confirmed that re-entrant piston bowl without a central projection is good for swirl and it increases total kinetic energy increase around the TDC. The re-entrant piston bowl geometry showed that reduction in emissions. Krishna Kaushik et al. [2] have studied about cylinder in flow and air fuel interaction on different piston bowls (Hemispherical bowl, Mexican hat, Double spherical combustion chamber bowl and Toroidal chamber bowl) of diesel engine by using computational fluid dynamics (CFD). They have concluded from their result that toroidal chamber bowl piston is the best one among the other types of pistons. Sucharitha et al. [3] have studied about different shapes of the pistons by using CFD analysis and they have confirmed from their CFD study that the piston geometry have made significant effect on the air flow characteristics during compression stroke. Raj et al. [4] have studied about different engine piston configurations such as flat piston, inclined piston, flat bowl piston and inclined offset bowl pistons. They have proved from their CFD study that the flat bowl piston engine has given best turbulent kinetic energy, tumble ratio and turbulent length scale and turbulent intensity which are the keys of imparting suitable air motion and increasing the engine efficiency. Ramachandran et al. [5] have studied diesel engine combustion and emission by theoretically and experimentally. From their study they have confirmed that MBP has given better performance, less emission experimentally and the same was proved by CFD analysis also. Both the experimental and CFD analyses have confirmed that MBP is an apt one for diesel engine. Payri et al. [6] have studied the different piston configurations and their flow characteristics. From the results it is concluded that the effect of bowl type piston plays a significant role to control mean and turbulence velocity fields. Channappagoudra et al. [7] have conducted an experiment in Kirloskar engine by using honge biodiesel. In this experimental study the piston bowl crown was modified by cutting number of grooves such as 3, 6 and 9-grooves to increase the air-fuel mixing rate. The test result revealed that the piston bowl crown with 6-groove configuration had given higher BTE, lower SFC, CO, HC when compared to the other configurations. Jonathan George Dolak et al. [8]have investigated the different piston configurations such as conventional bowl piston and stepped bowl piston in a Light duty engine at operating at low load. In this study bowl geometry, spray targeting, split fuel amounts, fuel efficiency and emission values were studied. The investigation results showed that the stepped bowl piston has given low soot formation and low CO emission. Sushma et al. [9] have studied computationally about the internal flow characteristics in the combustion chamber of a diesel engine for the different piston configurations and they have confirmed that geometry of the piston increases the air motion at the end of the compression stroke. The bowl piston type B has created high swirl inside the cylinder and it has provided higher efficiency when compared with other type of pistons. Manikalithas et al. [10] haveinvestigatedabout performance, emission and combustion characteristics of different diesel engine pistons such as bowl, dished, domed and trunked type by theoretically and experimentally.They have concluded from their study that the bowl piston crown had given better turbulence parameters such as turbulence intensity, turbulence kinetic energy and tumble behavior. Among various profiles, the maximum pressure with minimum heat of reaction during injection reduces NOx, HC and CO_2. This involves a better mixing inside the combustion chamber and increases the efficiency of combustion, peak pressure and power. In view of the above characteristics, the bowl piston crown is considered to be the optimum profile which can be used for analyzing various blends of fuel. The above literature surveys [1-11] have confirmed that the bowl piston configuration produces effective combustion results due to better swirl, squish and turbulence of air-fuel. The bowl piston geometry performed superior in many aspects when compared with other types of pistons. The bowl piston configuration has provided the better turbulent flow motion inside the cylinder and due to this turbulence, the air is uniformly distributed throughout the combustion chamber, prior to the fuel injection and it leads to better air–fuel mixing. In addition, the effect of turbulence increases the CP and temperature which in turn led to pre-ignition, provide better combustion and controlled engine exhaust gas emission level.Based on the above recommendations, EBP engine performance, emission and combustion values were taken from experimentally in Kirloskar engine by using 100%D. After that theoretical bowl piston was created in CFD based on the Kirloskar engine EBP dimensions and shape. CFD model bowl piston performance, emission and combustion values were taken from the CFD analysis. From the comparison point of view, theoretical CFD analysis bowl piston values are less than 5% deviation when compared with experimental EBP values. Based on this comparison results, the EBP piston dimensions and shapes was modified differently and analyised in CFD. From the CFD analysis best bowl piston dimensions and shapes details were found. Based on the CFD analysis the existing bowl piston dimension and shape was modified by machining process and used in the diesel engine. The EBP and MBP dimension and shape details are shown in Figure 1. In this experiment, the MBP performance, emission and combustion characteristics have been studied by using 100%D and compared with EBP.

2. METHODOLOGY

2.1. Physical and chemical properties of diesel.

The diesel physical and chemical properties of diesel are shown in Table.1 and the same were determined by using standard method and standard equipment. The results showed that the density of diesel is 0.837gm/c and kinematic viscosity is 3.067cSt respectively. Flash point, fire point of diesel is 47 ^oC and 58^oC respectively as well the calorific value of diesel is 42000 kJ/kg.

Table 1: Physical and chemical properties of diesel.

Property	Unit	100%D
Density @38^oC	gm/cc	0.837
Kinematic Viscosity@38^oC	cSt	3.067
Flash point	^oC	47
Fire point	^oC	58
Calorific value	kJ/kg	42000

2.2. Effect of spray and combustion on piston combustion chambers

The piston is the heart of the engine. Different types of pistons are used in the diesel engine now a days such as bowl, dished, dome and trunk type. The air-fuel mixture's squish, swirl, turbulent motion and combustion completely depend on the piston's profile. So change in piston profile can alter total kinetic energy (TKE), turbulence intensity, length as well as time scale of turbulence and tumble ratio to a greater extent. An increase in all the above mentioned quantities leads to an effective mixing of air-fuel. This increases the peak pressure on the piston during combustion and delivers more power without consuming more fuel. In general, this effective mixing reduces the formation of un-burnt fuel which in turn minimizes the formation of soot emission. The different types of pistons are used in the engine such as bowl, dished, dome and trunk type. The literature survey also [1-11]has proved that the piston with bowl configuration produces effective results when compared with other types. Figure 2(a) shows higher tangential velocity in almost all the regions due to the bowl configuration and the same has induced large and lengthy scale eddies. Vortex stretching breaks-up these eddies with high mixing and momentum transfer is initiated. Figure 2(b) confirms that dished type has comparably higher tangential velocity in the center regions. As a result, mixing and momentum transfer is restricted compared to bowl configuration. From the Figure 2(c), the turbulence eddies are found to be lengthy but small scale in dome piston. Therefore, they dissipate turbulent kinetic energy quickly and limit in the mixing of air and fuel. Figure 2(d) shows that trunk piston has created a higher tangential velocity in the left region. Hence, mixing and momentum transfer are limited in this model when compared with bowl configuration. Finally, it can be said that the bowl piston is a good choice of having proper mixing and better combustion. Hence it can provide better performance, combustion and less emission when compared with other type of pistons. The bowl piston geometry performs superior in many aspects and the depicted results provide a qualitative view of the major processes with the spray induced flow motion as well as its interactions in governing diesel combustion. The effect of turbulent nature inside the combustion chamber for various piston shapes resulted in the increased CP and temperature. Figure 2 (a) shows that fuel is uniformly distributed throughout the combustion chamber of bowl piston, eventually prior to fuel injection Furthermore, the maximum TKE is located near to the center of the engine combustion chamber. The bowl shaped profile has produced less pollution by providing a controlled temperature even at high pressure and significantly reduces the magnitude of the combustion peak pressure and temperature. The cause for the lower emissions resulted in relatively better air–fuel mixing and good fuel atomization. In addition, more complete combustion feature takes place by faster evaporation and vaporization of fuel spray droplets. Literature survey [1-11] also has recommended that the bowl piston as thebest one when compared with other types of pistons.Based on the above recommendations and CFD confirmation, the EBP combustion chamber was modified and a small level of volume was increased. The MBP profile can producethe highest squish, swirl, turbulent motion to a greater extent for air-fuel mixture and additional oxygen in the MBP volume will lead to effective combustion in the combustion chamber. In addition, this effective mixing increases the engine efficiency and reduces the formation of un-burnt fuel which in turn minimizes the formation of soot emission. Figure 1 shows the EBP and MBP dimensions and shapes.

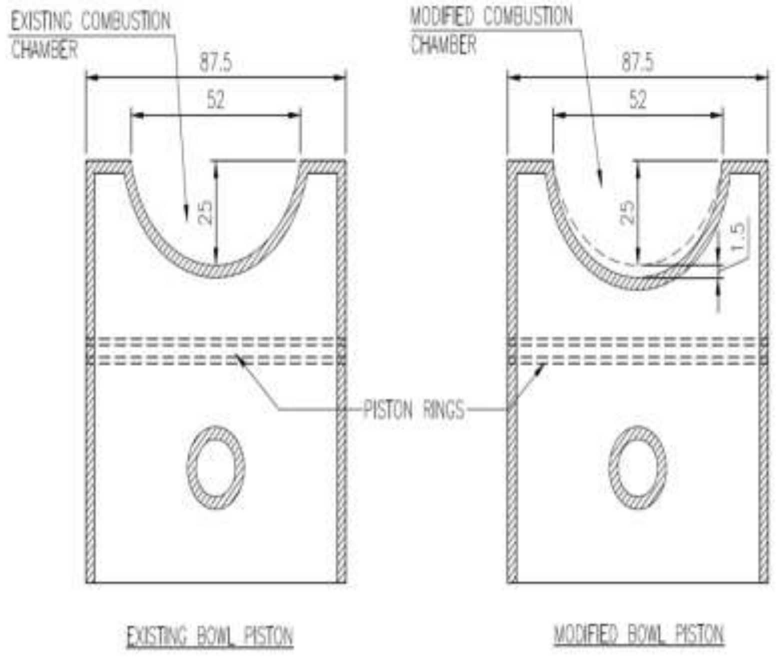

Fig. 1: Dimension details of existing bowl piston and modified bowl piston.

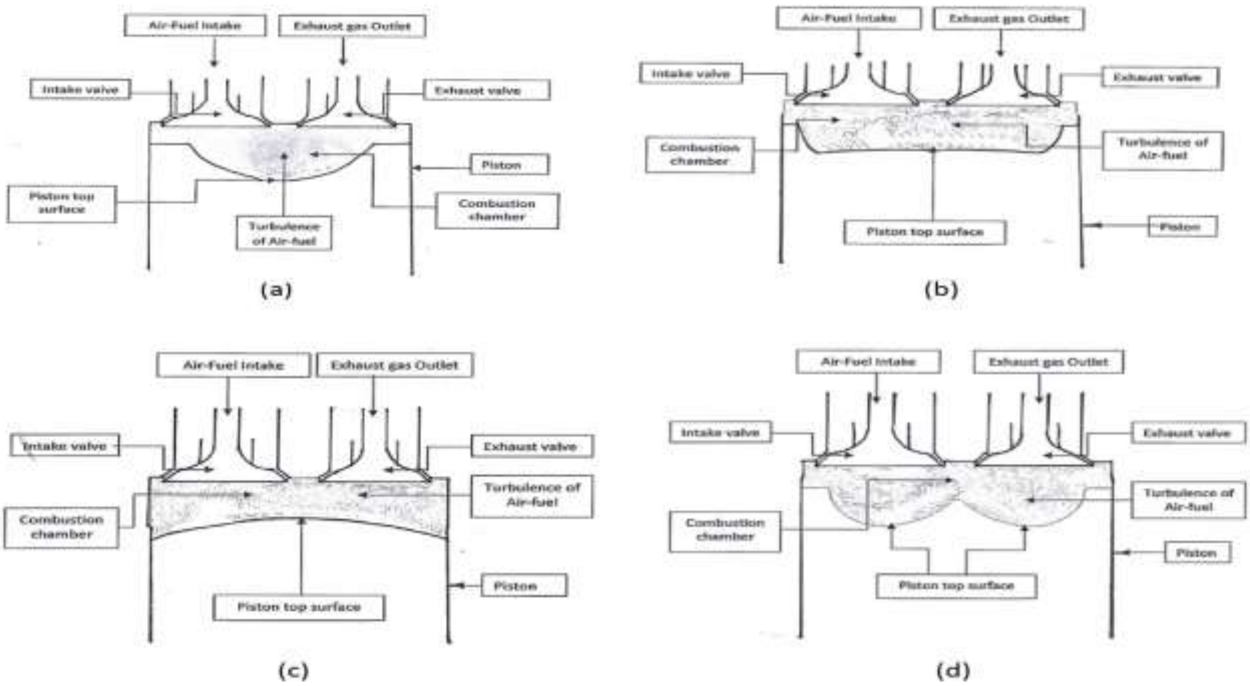

Fig. 2: Types of pistons and its arrangement.

(a) Bowl piston (b) Dished piston (c) Dome piston (d) Trunk piston

3. EXPERIMENTAL SETUP AND PROCEDURE

In this experiment MBP engine performance, emission and combustion characteristics were studied by using 100%D and compared with EBP engine. The following diesel engine and different equipments were used for measurements. (i) Four-stroke, vertical, water cooled, diesel engine (Kirloskar make) (ii) Eddy current dynamometer (iii) Fuel injection pressure measurement (iv) Cylinder pressure measurement (v) Data acquisition system (vi) Smoke meter and (vii) Exhaust gas analyzer. A fuel tank was connected to a burette to measure the time taken for fuel to be consumed. The necessary instruments were provided for pressure and crank angle measurements and these signals were interfaced to computer through engine indicator to plot P-Ɵ diagram. This engine was coupled to an eddy current dynamometer with a control system (BENZ make). The cylinder pressure was measured by the piezoelectric pressure transducer push mounted on the engine cylinder head and a crank angle encoder fitted on the flywheel. Both the pressure transducer and encoder signal were connected to the charge amplifier to condition the signals. A charge amplifier was used to condition the signals for further processing. The EBP engine fuel consumption, engine cooling water inlet and outlet temperature, speed, EGT and exhaust gas emission values were recorded for 100%D on different loads at warm-up period's ends and steady state condition. The similar procedure was repeated for MBP. The MBP engine performance, emission and combustion characteristics were discussed and compared with EBP in experimental results and discussion. The Kirloskar diesel engine, AVL gas analyser and AVL smoke meter technical details are shown in Table 2 & 3.

Table 2: Technical Specification of the diesel engine

Technical specification of diesel engine	
Engine make / Model	Kirloskar / SV1
Number of cylinder	Single cylinder
Type of injection	Direct injection
Type of cooling	Water cooled
Displacement volume	0.661 liters
Bore / Stroke length	87.5mm / 110mm
Fuel injection pressure	200 bar
Injection timing	23^{o} BTDC
Rated power	5.9 kW / 8 BHP
Method of loading	Eddy current dynamometer
Speed	1800 rpm

Table 3: Technical specification of Exhaust gas analyzer & Smoke meter

Make / model : AVL / 4000 Di gas analyzer & AVL / 437 Smoke meter			
Parameter	**Range of measurement**	**Resolution**	**Accuracy**
CO	0 – 10% Vol.	0.01% Vol.	± 0.2% CO
CO_2	0 – 20% Vol.	0.1%Vol.	± 1% CO_2
HC	0 – 20,000 ppm Vol.	1 ppm	± 30 ppm HC
NO_x	0 – 5,000 ppm Vol.	1 ppm	± 10 ppm NO_x
O_2	0 – 25% Vol.	0.01% Vol.	± 0.2% O_2
Opacity	0 – 100%	0.1%	± 1% of full scale
Absorption (k-value)	0 – 99.99 $^1/_m$	$0.01^1/_m$	± 0.1 $^1/_m$

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

In this experiment, combustion chamber of EBP has been modified for better swirl, better squish and better turbulent motion of the air-fuel mixture. The MBP engine performance, emission and combustion characteristics have been studied by using 100%D and it has been compared with EBP. From the comparison of the experimental results, it has been concluded that MBP has given better performance, less emission and better combustion by using 100%D when compared with EBP.

4.1 Engine performance analysis

The variation of BTE with engine all loads for 100%D are shown in Figure 3 for EBP and MBP. From the test results, the higher BTE is found for MBP at a load of 80% and100% when compared with EBP for 100%D. From the test results, the MBP has given higher BTE at an engine load of 80% and 100% when compared with EBP for 100%D. The BTE is found to be 30.94%, 31.92% at engine load of 80% and 100% for MBP whereas the corresponding value of EBP is 29.56%, 31.62%. The higher BTE is the outcome of the decrease in SFC and better combustion occurred in the modified combustion chamber (MCC) and it is due to better squish, swirl and turbulent motion of air fuel mixing [4, 6].

Figure 4 shows the variation of EGT with engine all loads for 100%D for EBP and MBP. From the results it has been confirmed that the higher EGT has been obtained at engine all loads for MBP when compared with EBP for 100%D. The increase in EGT is because of better combustion occurred in the MCC. The main reason for better combustion is as a result of excess air in the

MCC, effective mixing air-fuel and better turbulent motion of air-fuel in the MCC. The higher EGT is found to be 456°C at an engine full load condition for MBP whereas the corresponding value of EBP is 444°C for 100%D.

4.2 Engine emission analysis

The variation of HC emission of 100%D and engine all loads are shown in Figure 5 for EBP and MBP respectively. The results show that HC emission values have decreased all loads for MBP by using 100%D when compared with EBP. The reduction of HC is due to complete combustion occurred in the MCC. The main reason for complete combustion is due to the presence of excess air in the MCC and better mixing of air-fuel in the MCC [1, 7].

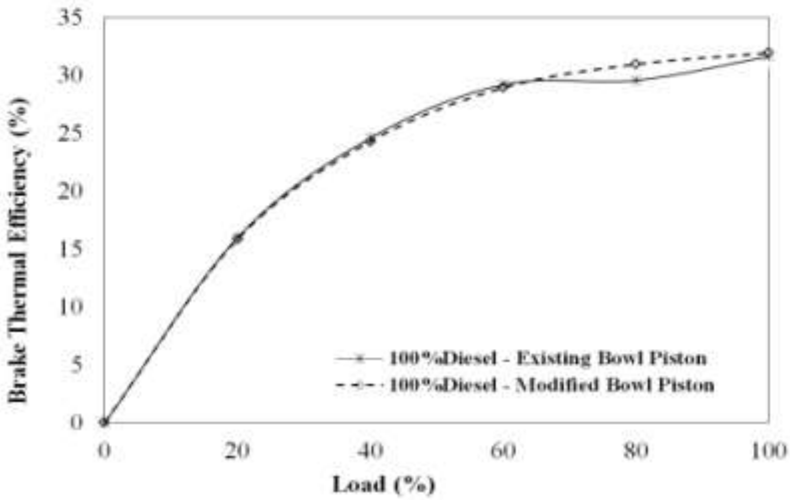

Fig. 3: Variation of brake thermal efficiency with loads.

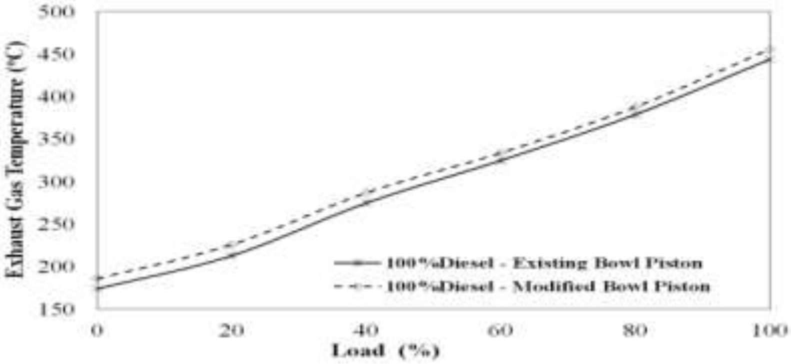

Fig. 4: Variation of exhaust gas temperature with loads.

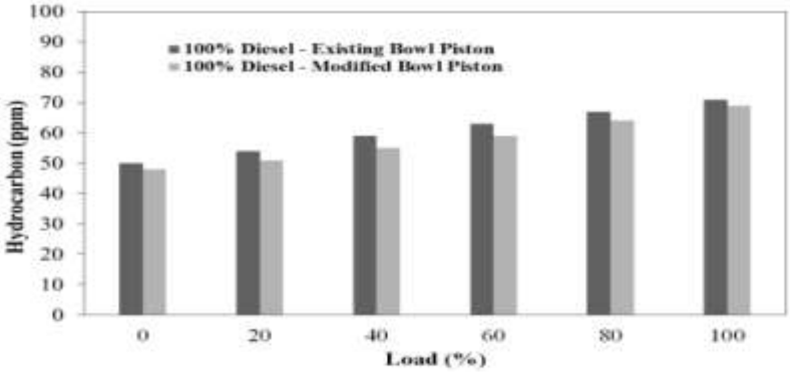

Fig. 5: Variation of hydrocarbon with loads.

Figure 6 shows the variation of CO emission of 100%D and engine all loads of EBP and MBP. From the results it has been confirmed that CO emission level has decreased for MBP by using 100%D when compared with EBP at all engine loads. The main reason for low CO emission is due to better combustion occurred in the MCC and reduction of HC emission level[1, 7].

Figure7 shows the variation of CO_2 emission of 100%D of EBP and MBP for engine all loads. It is observed from the graph that CO_2values have increased for all loads of MBP when compared with EBP for 100%D. The MBP has given higher CO_2 emission when compared with EBP for 100%D and the higher CO_2 is an indication of the complete combustion of diesel in the MCC. This is due to the presence of excess oxygen in the MCC and better swirl, turbulence of air fuel in the MCC and this supports the higher value of EGT.

The variation of NO_x emission of 100%D is shown in Figure 8 for engine all loads of EBP and MBP.It has been concluded from the results that MBP has given higher level of NOx emission at all engine loads by using 100%D when compared with the EBP. It is observed from the results that maximum NO_x value has been obtained is 660ppm at engine full load condition for MBP and the corresponding value of the EBP is 649ppm. The main reason for increases in the NO_x emission level is due to better combustion occurred in the MCC and higher EGT during combustion time [1, 7].

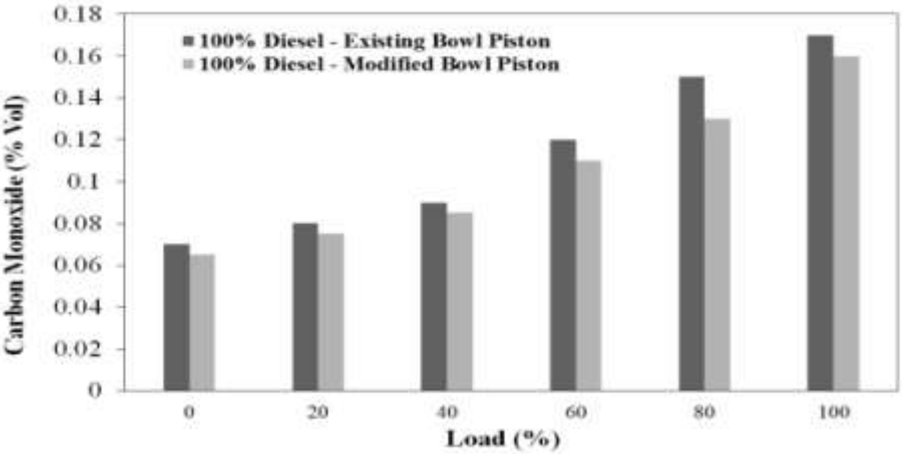

Fig. 6: Variation of carbon monoxide with loads.

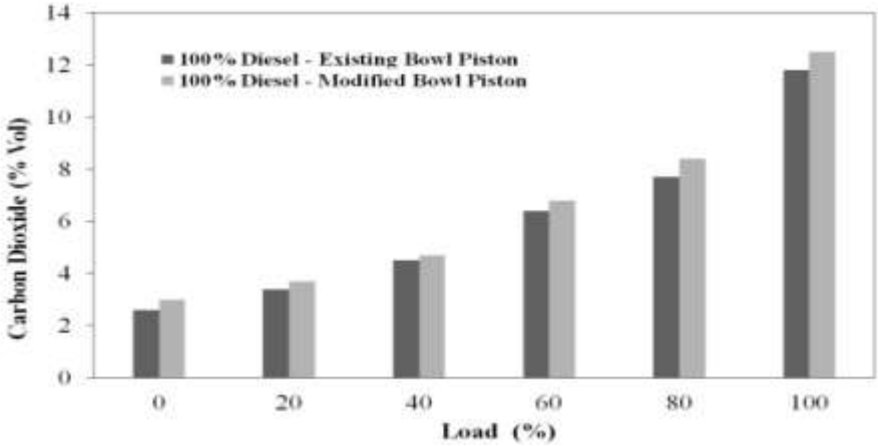

Fig. 7: Variation of carbon dioxide with loads.

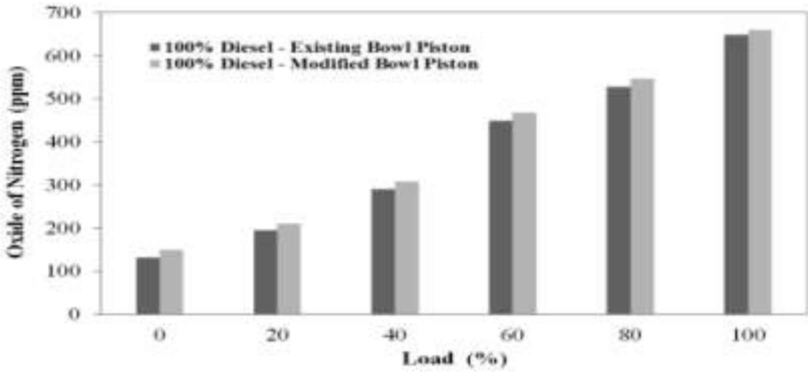

Fig. 8: Variation of oxide of nitrogen with loads.

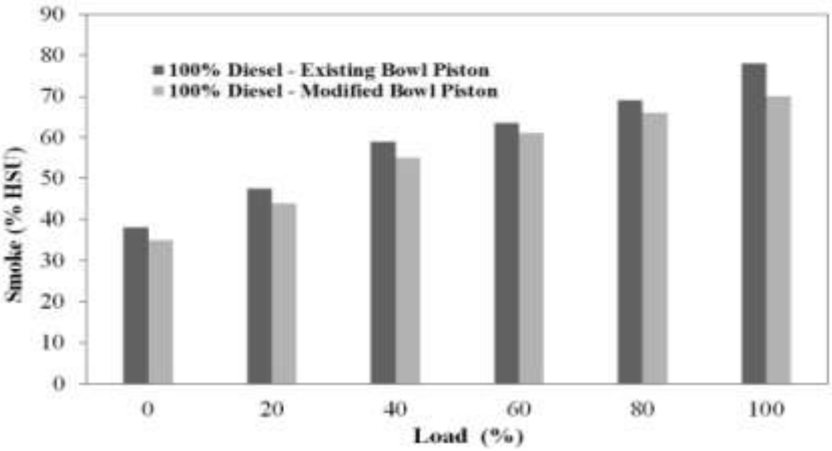

Fig. 9: Variation of smoke with loads.

The variation of smoke with respect to engine all loads of 100%D is shown in Figure 9 for EBP and MBP respectively.From the comparisons of EBP and MBP smoke range, it has been concluded that 100%D has given lower smoke for MBP at all engine loads when compared with EBP. The main reason for lower smoke of MBP isbecause of better combustion occurred in MCC and it may be due to the excess of oxygen in the MCC and better swirl, better squish and better turbulent motion of air-fuel mixing in the MCC. The 70% smoke has been let out at engine full load condition for MBP and the equivalent value of EBP is 78% for 100%D.

4.3 Engine combustion analysis

Figure 10 shows the comparison of the crank angle with respect to CP at engine full load condition for EBP and MBP by using 100%D. In a diesel engine, the CP is based on the mixing capacity of air-fuel mixture during combustion and the combustion rate of fuel in the initial stage. It has been concluded from the results that the MBP has given higher CP when compared with EBP for 100%D. The maximum CP of MBP is 56.83bar and the corresponding value of EBP is 50.11bar respectively at engine full load condition.The main reason for increase in CP is because of better combustion happened in the MCC and it's due to better swirl, better squish and better turbulence of air-fuel mixture. Further reason is that the higher of amount fuel has been burnt in the premixed combustion during ignition delay [5].

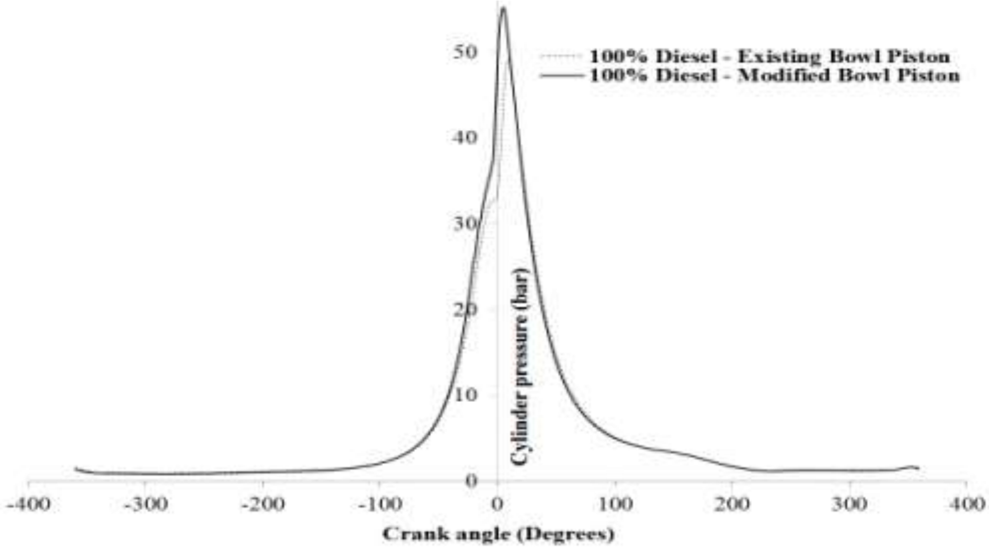

Fig. 10: Variation of cylinder pressure with crank angle.

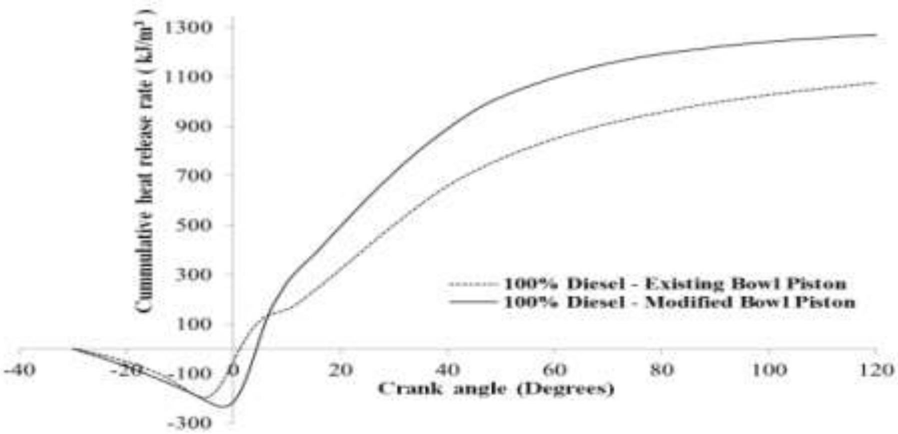

Fig. 11: Variation of cumulative heat release rate with crank angle.

Figure 11explains the variation of crank angle with respect to CHRR at engine full load condition of 100%D for EBP and MBP. Generally the amount of heat release rate is depends onthe calorific value of the fuel and air-fuel mixing rate in the combustion chamber during combustion. From the results, it has been observed that MBP has given higher CHRR for 100%D when compared with EBP. The MBP has given CHRR as 1271kJ/m^3 and the corresponding value of EBP is 1076kJ/m^3. The main reason for increase in the CHRR is better combustion occurred in the MCC and it may be due to higheratomization, higher vaporization, higher volatility of diesel and better squish, swirl and the turbulent motion of air-fuel mixture in the MCC [5].

5. CONCLUSIONS

The main aim of this present investigation is to reduce the pollutant level in the atmosphere by providing better combustion of air-fuel. Based on this, theEBP has been modified and used as a MBP in diesel engine. The performance, emission and combustion characteristics have been found for MBP by using 100%D and compared with EBP. From the comparison results the following points were concluded.The MBP has given lower SFC, higher BTE at engine load 80% and 100% and the MBP has given higher EGT at all loads when compared with EBP. The MBP has given lower HC, CO, smoke at engine all loads when compared with EBP. However the MBP has given higher NO_x, CO_2at engine all loads.The CP and CHRR have also increased for MBP when compared with EBP at engine full load condition. From the above experimental results, it has been concluded that engine performance, emission and combustion point of view of MBP is anapt replacement of EBP.

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REFERENCES

1. Prasad, B.V.V.S.U., Sharma, C.S., Anand, T.N.C. and Ravikrishna, R.V. 2011. High swirl-inducing piston bowls in small diesel engines for emission reduction. Applied energy. 88(7): 2355–2367.

2. Krishna Kaushik, P. and Sai Swaroop, D. 2014. Effect of piston bowl geometry on various fluid flow patterns. International journal of engineering research &technology. 3(5): 2186-2189, ISSN: 2278-0181.

3. Sucharitha, G. and Kumaraswamy, A. 2013. Analysis on three dimensional flow of direct injection diesel engine for different piston configuration using CFD. Indian journal of science and technology. Vol.6 (5S), 4748-4753, Print ISSN: 0974-6846, Online ISSN: 0974-5645.

4. Raj, ARGS., Mallikarjuna, J.M. and Ganesan, V. 2013.Energy efficient piston configuration for effective air motion - A CFD study. Applied energy. 102:347-354.

5. Ramachandran, N., Kalil Rahiman, M. and Manikalithas, P. 2015. Investigation on combustion and emission analysis in a CI engine using CFD. International journal of applied engineering research. 10: 252-260, ISSN: 0973-4562.

6. Payri, F., Benajes, J., Margot, X. and Gil, A. 2004. CFD modelling of the in-cylinder flow in direct-injection diesel engines. Computers & Fluids. 33: 995-1021.

7. Channappagoudra, M.N., Sunil Thaned, Banapurmath N.R., Ramesh, K.and Manavendra, G. 2013. Effect of swirl on DI diesel engine operated with honge biodiesel. International journal of engineering research and applications. 3(6): 595-60, ISSN 2248-9622.

8. Jonathan George Dolak, Yu Shi. and Rolf D Reitz. 2010. A Computational investigation of stepped-bowl piston geometry for a light duty engine operating at low load. SAE International. DOI- 10.4271/2010-01-1263.

9. Sushma, H. and Jagadeesha, K.B. 2013. CFD modeling of the in-cylinder flow in direct-injection diesel engine. International journal of scientific and research publication. 3(12):1-7, ISSN 2250-3153.

10. Manikalithas, P., Venkatachalam, R., KalilRahiman, M. and Bharathiraja, M. 2016. Investigation of fluid flow, turbulence and combustion for various piston configurations in a compression ignition engine using CFD modeling. Asian Journal of research in social science & humanities. In press.

11. Harshavardhan, B. and Mallikarjuna, J.M. 2013. CFD Analysis of in-cylinder flow and air-fuel interaction on different combustion chamber geometry in DISI engine. International journal on theoretical and applied research in mechanical engineering. 2(3): 104-108, ISSN: 2319-3182.

12. Heywood. J.B, 1988.Internal combustion engines fundamental. Mc Graw-Hill. New York.

13. Stephen. R.T., 2000.An introduction of combustion. Mc Graw-Hill. New York.

14. Ganesan. V, 2002, IC Engines. Tata Mc Graw-Hill. New Delhi.

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